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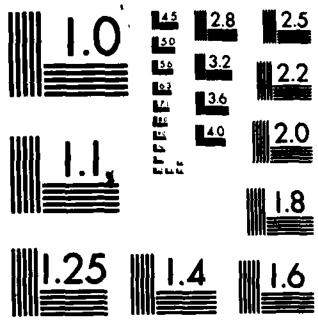

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New materials, new means of fabrication, and new device structures for high density magnetic bubble devices are being pursued. A large portion of the research is directed at ion implanted contiguous disk devices which offer sixteen times the bit density of permalloy devices now being sold by U.S. OEM manufacturers. The effects of ion implantation on garnet are being studied with the goal of developing improved garnet materials and fabrication techniques for submicrometer bubble size devices. The behavior of charged walls which act to propagate the bubble domains in these devices is being

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investigated and correlated with the ion implantation, mask pattern design, and device performance. Unique work with transmission electron microscopy in ion implanted garnets has enabled us to directly observe structural changes produced by ion implantation in patterned devices. Micrographs clearly show the importance of implantation mask champher on the strain profile at pattern edges, and previously ~~unobserved~~ extended defect structures have been observed. During the past year 0.5 μm bubbles were propagated in ion implanted contiguous disk devices.

In addition to the work on field-accessed ion implanted contiguous disk devices, work is being carried out on current-access perforated-sheet technology which offers four times the bit density of presently manufactured devices and order of magnitude higher data rate. During the past year bubble logic gates were demonstrated in this technology.

Finally a current-access ion-implanted device structure which offers the high density of field-access contiguous-disk technology and the high performance of current-access technology is being pursued. During the past year propagation structures for this technology were fabricated and preliminary tests are quite promising.

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"A PROGRAM OF RESEARCH ON MICROFABRICATION TECHNIQUES FOR VLSI MAGNETIC DEVICES"

PROGRESS REPORT

Sept. 30, 1982 - Sept. 29, 1983

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Table of Contents

1. Introduction

The Air Force Office of Scientific Research has been funding a research program entitled, "A Program of Research on Microfabrication Techniques for VLSI Magnetic Devices," since September 29, 1980. This report describes the progress made on this research project during its third year.

Work under this grant is directed primarily at the development of new magnetic bubble materials, new techniques for fabricating bubble devices, and on new device structures. The emphasis has been directed at obtaining materials, techniques, and structures which can be used with submicrometer domain sizes. A large effort has been directed at the development of garnet materials and ion implantation techniques for ion implanted bubble devices. Ion implanted devices offer four to sixteen times higher bit density than currently manufactured permalloy devices and are seen by most bubble memory manufacturers as the most likely successor to permalloy technology. In addition we are pursuing current-access bubble technology which offers order of magnitude higher performance than either permalloy or field-access ion implanted technology, as well as a current-access ion implanted technology, invented at Carnegie-Mellon University, which combines the high density attributes of conventional ion-implanted technology with the high performance of current-access. Work on amorphous materials for magneto-optic recording applications originated with support from AFOSR grant 80-0284, but now is supported by the Rome Air Development Center and the General Electric Corporation. Work on amorphous bubble materials has progressed so far that materials suitable for 0.5μm bubbles can be reliably produced; however, device work on these materials is being held up until additional funding is obtained.

The work described in this report is complementary to U.S. industrial bubble efforts. The materials, techniques, and structures such as ion implanted devices and current access devices being researched at Carnegie-Mellon University are not presently pursued by either Motorola or Intel, the two U.S. OEM manufacturers of bubble memories, but both have indicated interest in these new technologies for future generation devices. Motorola currently provides support for one graduate student in the program and has repeatedly used our expertise and facilities to solve manufacturing and design problems. Negotiations are currently underway with Intel for support of the program. Bell Laboratories is addressing ion implanted devices, but they have typically focused on larger bubble size devices than we at CMU.

Furthermore, as evidenced by references in their publications, they frequently make use of our more exploratory and fundamental work. Although Bell Laboratories has at times had programs on current access technology, to our knowledge, today they have no program in this area which we feel offers significant performance advantages. Hence the bubble program at CMU is properly classified as an exploratory research effort to develop future generation bubble technology offering order of magnitude improvements in bit density and/or performance over current generation technology. It is complementary to industrial bubble efforts and the results of the research at Carnegie-Mellon University are used by the industrial firms involved in bubble technology.

The program supported by AFOSR Grant 80-0284 has been tremendously successful. As indicated above all industrial efforts in bubble technology in the U.S. have made use of research results from this program. Furthermore faculty working on this program act as consultants to industry in the bubble technology area and students educated with grant support from this program have been hired by U.S. firms involved in bubble technology. In addition the Rome Air Development Center and more recently NASA have funded contracts which can be traced to work initiated under this grant. Since the beginning of the grant there have been 14 journal publications and three Master's Degree theses which resulted from the grant support. Below are contained progress summaries by area and detailed reports from selected areas, as well as appended publications.

2. Garnet Bubble Materials and the Effects of Ion Implantation on them

2.1 The Effects of Deuterium and Oxygen Implantation on the Magnetic Parameters of Garnet Films

An extensive and in-depth study of the effects of deuterium and oxygen implantation on films has been underway. Deuterium implantation is of particular interest because it is found the change in anisotropy energy produced by increasing implant doses does not saturate as it does for heavier ions. Hence deuterium implants can be used to produce a larger anisotropy field change than heavier ions. For small bubble materials, a large anisotropy field change is needed. Oxygen implants are useful for producing a more uniform strain profile than is easily achievable with deuterium implants alone.

During this past year we published[1] extensive data on the temperature dependences of the magnetic parameters in the ion implanted layers of garnet. The total implantation-induced uniaxial anisotropy field change ΔH_E and that portion attributed to the magnetostriction ΔH_σ were measured in deuterium implanted films as functions of temperature, and it was found that magnetostrictive anisotropy typically accounted for less than 50% of the total anisotropy field change up to temperatures as high as 160°C. ΔH_σ decreased approximately linearly with temperature. In oxygen implanted films, by comparison, magnetostriction was found to account for nearly all the anisotropy change.

In the deuterium implanted films no saturation in ΔH_E with increasing implant induced strain was observed up to the highest strain measured, 2.2%. In oxygen implanted films, on the other hand, saturation was observed with strains of about 1%. The ratio of magnetostriction to magnetization λ_{111}/M_s in deuterium implanted films was found at room temperature to increase with low implant doses and then decrease as the implant dose was raised above a moderate level. However, the temperature dependence of λ_{111}/M_s in the more heavily implanted films was typically less than that of films with more moderate doses. Thus at high temperatures λ_{111}/M_s was larger in heavily implanted films than in lightly implanted films.

The temperature dependences of ΔH_E, ΔH_σ, and λ_{111}/M_s in the deuterium implanted films had not previously been reported. The data, are of direct relevance to understanding the temperature dependence of ion implanted bubble devices.

Correlations of device performance as a function of increasing temperature with these data should provide insight into how to optimize implants for wide temperature range operation.

The reasons for the observed differences in the effects of deuterium and oxygen implantation are not yet well understood. The larger nuclear energy loss of a high energy oxygen atom as it strikes the garnet substrate would be expected to produce different effects than the low nuclear energy loss suffered by a light ion such as deuterium. Furthermore, since much higher doses of deuterium are required to produce similar changes in anisotropy, deuterium implanted films have a much higher percentage of implanted ions present than oxygen implanted films. Thus there is the added possibility that some sort of chemical effects might arise from the presence of deuterium. However, no detailed explanation has yet been provided which adequately explains the measured differences of the effects of implantation with these two ions. We are continuing to work on this problem.

More detailed descriptions of this work are contained in Attachments 1 and 2 of this report.

2.2 Charged Wall Formation in Ion-Implanted Garnets

We have been conducting an extensive study of charged walls in ion implanted garnets. As a result of these studies we have been able to correct previous theories which asserted that charged walls formed because of demagnetizing effects and exhibited anisotropic behavior primarily because of magnetocrystalline anisotropy[2]. We have shown that anisotropic stress relaxation at boundaries between implanted and unimplanted regions produces, via magnetostriction, a uniaxial anisotropy parallel to the boundary which is responsible for *charged wall formation.* Demagnetizing effects, rather than helping to form the charged wall, actually oppose its formation. Moreover, although magnetocrystalline anisotropy contributes to the anisotropic behavior of charged walls, our results show that the magnetostriction giving rise to the uniaxial anisotropy at the boundaries is anisotropic and typically dominates over magnetocrystalline anisotropy in causing anisotropic charged wall behavior. These new findings explain why others, who attempted to reduce anisotropic behavior of charged walls by reducing magnetocrystalline anisotropy, failed[3]. They were ignoring the effects of anisotropic magnetostriction. Recently, after our publication explaining the effects of anisotropic magnetostriction[4], workers at Bell Laboratories[5] and NEC[6] have published work on garnets containing dysprosium and which have more isotropic magnetostrictive properties. Their measured results confirm our predictions.

More recently we have developed a numerical model with which it is possible to accurately calculate all the stress components near boundaries between implanted and unimplanted regions. In turn, we then are able to calculate the resultant magnetostrictive anisotropies. To our knowledge we are the first to explicitly account for shear stresses[4] in addition to longitudinal strain and compression. Early results suggest that shear stresses are large in typical device patterns and may cause some important effects. Further work in this area is planned.

To test our numerical model, we are designing a test device with implanted and unimplanted regions having a variety of regular shapes which may be readily modeled on the computer. We plan to use the magneto-optic photometer[7] to measure the anisotropies around these patterns and compare experimental results to the model.

More detailed accounts of work in this area may be obtained from Attachments 3 and 4 to this report.

2.3 The Effects of Ion Implantation and Thermal Annealing on the Physical Properties of Garnet

Amorphization produced by ion implantation and subsequent crystallization produced by thermal processing in liquid phase epitaxial (LPE) garnet films have been investigated by transmission electron microscopy[8,9]. A special technique involving physical polishing and ion milling was used for producing ultra-thin cross-sections of the LPE garnet films. To our knowledge no one else has such capabilities. It was found that the amorphization process evolves in four separate stages: (1) an implanted (crystalline) band, delineated by the implantation strain profile, forms at doses of about $0.5 \times 10^{16} D_2^+/cm^2$ and $0.95 \times 10^{14}\ 0^+/cm^2$, (2) isolated amorphous regions of about 10nm in diameter form at doses of about $1.0 \times 10^{16} D_2^+$ and $1.9 \times 10^{14} 0^+/cm^2$, (3) the amorphous regions merge to form a continuous band below the implanted surface at doses of about $3.0 \times 10^{16} D_2^+/cm^2$ and $5.7 \times 10^{14}\ 0^+/cm^2$, and (4) this band expands to the implanted surface at larger doses. It was found that amorphization is caused by implantation with oxygen and not by deuterium, but prior implantation with deuterium causes amorphization to occur at lower oxygen doses by increasing the strain.

The crystallization process was found to evolve in three separate stages: (1) small crystallites, about 10 nm in size, form throughout the entire amorphous band after annealing for 30 minutes at 350°C, (2) larger crystallites nucleate and grow from the

implanted surface and the amorphous/crystalline interface after annealing for 1 hr at 450°C, and (3) these crystallites grow in size until they merge to form a continuous polycrystalline layer. Some epitaxial regrowth of the monocrystalline into the amorphous region is also observed.

In samples implanted through a mask pattern, not only the strain profile as a function of depth into the sample, but also laterally at pattern edges was studied[10]. we found that the sharpness of the mask edge clearly affected the sharpness of the strain profile at the pattern boundary. Based upon our investigations of the effects of strain profiles on charged walls (see Section 2.2), we expect that such different strain profiles will have a strong effect on charged wall behavior.

The studies of samples implanted through a mask also revealed a previously unobserved defect structure in samples implanted with heavy doses of deuterium. As indicated above, deuterium alone does not produce amorphization of the lattice, but we have observed extended defects which run from the implanted film surface to the bottom of the implanted region (see Fig. 1) in masked samples implanted with 4.5 x 10^{16} D_2^+/cm^2. These defects do not appear in uniformly implanted samples and we believe they form to relieve the non-uniform stress introduced by the heavy deuterium implants. Currently we believe the defects to be dislocations, but studies are underway to prove or disprove this hypotheses.

Fig. 1 A cross-sectional transmission electron micrograph of extended defects in a garnet film implanted with $4.5x10^{16}$ D_2^+/cm^2 in a selected region. The defects extend from the surface of the film to the strain contour delineating the implanted region.

3. Amorphous Magnetic Materials

Work on amorphous magnetic materials for magneto-optic recording applications is now being supported by research contracts from the General Electric Corporation and the Rome Air Development Center[11]. It may be justifiably stated that work initiated under AFOSR Grant 80-0284 led to these contracts.

Work on amorphous bubble materials progressed under the first two years of AFOSR Grant 80-0284 to the point that materials for 0.5μm bubbles could be routinely deposited by r.f. sputtering. A promising opportunity now exists for some creative research on device structures which may be used to propagate such small domains in these materials. Unfortunately funding limitations have made it impossible for us to pursue this area of research during this past year. We hope t pursue this area of research in the future when additional funds are available, or a our work on ion implanted garnet materials and devices is transferred to industry.

4. Magnetic Bubble Devices

Work on actual bubble device structures at Carnegie-Mellon University is directed at the development of new device technologies offering order of magnitude improvements in bit density and performance over permalloy devices now in manufacturing at Motorola, Intel, Bell Laboratories, Fujitsu and Hitachi. We have made major contributions to ion implanted contiguous disk bubble technology and it continues to be viewed as the most likely successor to permalloy technology because it offers four to sixteen times the bit density at the same minimum lithographic linewidth. In addition to the work described above in Sections 2 on the effects of ion implantation on garnet and on the behavior of charged walls in implanted garnets, we have been pursuing the fabrication of contiguous disks devices using submicrometer bubble sizes. This work is described below in Section 4.1.

In addition to the work on field-access ion-implanted devices we have also been pursuing two current-access technologies which offer not only higher bit density than permalloy technology, but higher performance as well. Presently manufactured permalloy devices use a rotating field generated by passing current through two orthogonal coils wrapped around the bubble memory chip. Data rate is limited by the inductance of the coil, not by bubble materials characteristics. However, current carrying conductors on the chip can be used to propagate bubbles as well, and make possible order of magnitude improvements in data rate. We are pursuing current-access perforated-sheet technology[12] for use in the input and output path of block replicate bubble chips which use field access contiguous disk technology for high density storage. The high data rate of the input and output paths will make possible fast access while the use of field access for data storage will keep on-chip power dissipation to acceptable levels. The perforated sheet technology also makes possible data manipulation through bubble logic, further improving bubble memory performance in systems. Work on current access perforated sheet devices is described in Section 4.2 below.

A novel current access device structure with potential for order of magnitude improvements in both bit density and performance is the current access ion implanted device structure, which was invented at CMU and worked on under this grant. Although at an earlier stage of development than either field access contiguous disk or current access perforated sheet devices, this new structure shows great potential. It is described in Section 4.3 below.

4.1 Ion Implanted Contiguous Disk Magnetic Bubble Devices

Ion-implanted contiguous disk devices offer four to sixteen times the bit density of presently manufactured permalloy bubble devices[13,14], because their minimum lithographic feature size is larger and because rotating drive field requirements are lower. Our research on these device is focussed primarily at the demonstration of devices using submicrometer sized domains. We are trying to establish scaling rules for the technology and to push the limits of high density storage.

During this past year we fabricated full function bubble memory chips for 0.5μm, 1μm, and 2μm diameter bubbles, as well as some test chips for evaluating new bubble device functions including a block replicate-transfer gate. Testing of these devices is currently being carried out and ways to improve the device functions are being investigated. A notable finding is the discovery that implantation through a SiO_2 overcoat improves device operating margins and reduces the minimum drive field. Also, although the data is preliminary, we have now successfully propagated 0.5μm diameter bubbles.

More details of the fabrication processes used and the test results obtained on field-accessed contiguous-disk devices can be obtained from Attachment 9.

4.2 Hybrid Current-Access Perforated-Sheet/Ion-Implanted Contiguous-Disk Magnetic Bubble Devices

Current-access perforated-sheet bubble devices offer four times the bit density of presently manufactured permalloy devices and order of magnitude improvements in data rate.[12] Unfortunately on-chip power dissipation is high and becomes worse as bubble size is reduced.[15] To circumvent the problem of high power dissipation and retain the advantage of high data rate, we have been investigating the design and fabrication of hybrid chips which use field-accessed contiguous-disk technology for memory and current-access perforated-sheet technology for input/output tracks and on-chip logic.[16,17] Since only a small area is needed for input/output tracks, average on-chip power dissipation may be kept low. With clever chip architecture design it is possible to obtain high performance even when the memory section of the chip is slow, when the input/output tracks are run at high data rate.[16,17]

During this past year we tested a first generation test chip, iterated on the design and fabricated a second test chip. Testing of the second chip is now underway. Early results show that our bubble-bubble interaction logic gate operates reliably over

a narrow bias margin range. We are presently trying to understand what is limiting the margin and widen it with improved fabrication and design. More details of the fabrication, design and test of these devices may be obtained from Attachments 10,11,12 to this report.

4.3 Current-Access Ion-Implanted Magnetic Bubble Devices

Current-access ion-implanted devices were invented at CMU by Professor Kryder and have been worked on under AFOSR Grant 80-0284.[18]. This device stucture uses the large-linewidth structure of ion implanted contiguous disk devices to produce an extremely high density storage device and the on-chip conductors of current-access perforated-sheet technology to obtain high performance. Earlier work on this structure pertained to a demonstration of bubble circulation around an isolated disk, but not to bubble propagation around a shift register.[18].

During this past year actual propagation patterns for the devices were fabricated and testing is currently underway. Studies have been conducted to try to optimize ion implantation conditions by implanting identical chips from a single wafer with different implantation doses and observing field accessed propagation of bubbles. The best results to data provide 15% margins at 65 Oe rotating in-plane drive field. Our next step will be to complete the fabrication of these devices by adding the current sheets so that current-access may be demonstrated.

More details of the fabrication and testing of these devices may be obtained from Attachment 13.

5. Publications Under Grant AFOSR 80-0284

1. J. J. Fernandez de Castro and M. H. Kryder, "Magneto-Optic Measurements of the Effects of Crystalline Anisotropy in Ion-Implanted Layers of Garnet," Paper BB-2, Magnetism and Magnetic Materials Conf., Dallas, Nov. 11-14 (1980).

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15. T. Yoshiie, C. L. Bauer and M. H. Kryder, "Investigation of Amorphization and Crystallization Processes in Ion-Implanted Garnet by Transmission Electron Microscopy," to be published in J. Appl Phys.

16. C. S. Krafft and M. H. Kryder, "The Temperature Dependence of Anisotropy Fields in Deuterium Implanted Garnet Films," paper AB-07, Magnetism and Magnetic Materials Conference, Pittsburgh, Nov. 8-11, 1983; to be published in J. Appl. Phys.

17. A. K. Singh, C. L. Bauer and M. H. Kryder, "Direct Observation of Implantation Profiles in Garnet by Transmission Electron Microscopy," Paper AB-09, Magnetism and Magnetic Materials Conference, Pittsburgh, Nov. 8-11, 1983.

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